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EFFECT OF VARIABLE STATOR AREA ON PERFORMANCE OF A SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING

V — Stator Detailed Losses With 70-Percent Design Area

by Herman W. Prust, Thomas P. Moffitt, and Bernard Bider

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

The turbine is being investigated at stator area settings of 70, 100, and 130 percent of design. This report presents the experimental and analytically predicted results for the stator having a closed (70 percent) area setting and compares these results with similar results obtained for the design (100 percent) area and open (130 percent) area settings. The final results are presented in terms of kinetic-energy loss coefficients as a function of velocity level. The experimental losses were close to those predicted analytically and indicate a stator efficiency of about 96 percent.

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SUMMARY

As part of a single-stage variable stator area turbine program, an investigation of the kinetic-energy loss coefficients of the stator in a closed setting was made. For this setting, the channel exit orthogonal at the mean section was decreased to 70 percent of the design area setting. Experimental and analytical loss coefficients were obtained for the subject closed stator and compared with similar values for the reference design and open stators.

The experimental values of efficiency for the subject closed stator agreed well with predicted values and varied from about 95.5 percent to 96.5 percent over the range of exit velocity tested. The higher efficiency occurred at the higher velocity.

The same experimental value of efficiency of about 96.5 percent was obtained at design exit Mach number as the stator area was varied from 130 to 100 to 70 percent of design. This efficiency is close to the predicted results, which indicated a decrease in efficiency from about 97 to 96.5 percent as the stator was closed from 130 to 70 percent of design area.

INTRODUCTION

Advanced aircraft such as the supersonic transport require high engine temperatures to achieve their performance goals. The turbine blading for this type of application is characterized by thick, blunt profiles and low solidity because of cooling considerations. In addition to the performance requirement at design conditions, it is important in some instances that high performance be maintained at one or more off-design operational modes (ref. 1). One method considered (refs. 1 and 2) to improve off-design engine performance is the use of adjustable turbine stators. This feature would permit the turbine to operate at a fixed pressure ratio over a range of equivalent weight flow and thereby allow the engine to operate closer to optimum cycle conditions.

One phase of the turbine research program at Lewis Research Center is the investigation of turbine performance over a range of stator areas. The turbine being used in this investigation is a 30-inch (0.762-m) cold air turbine designed with physical features typical of those required of a turbine for high engine temperature application. The design and overall stator performance of the turbine are described in reference 3. The stator boundary-layer characteristics are presented in reference 4, and stage performance data are presented in reference 5. Two additional stator assemblies were fabricated to provide outlet flow areas of 70 percent and 130 percent of design. The investigation includes overall stator tests, stator outlet surveys, and stage performance tests similar to those described in references 3 to 5 for the design stator configuration. The results obtained with the 130 percent stator have been completed and are described in references 6 to 8, and the overall performance results for the 70 percent stator have been completed and are described in reference 9.

This report presents detailed experimental and analytically predicted performance results including kinetic-energy loss coefficients for the 70-percent flow area stator. (Efficiency, in terms of kinetic energy, may be obtained by subtracting these coefficients from unity.) In addition, kinetic-energy loss coefficients for this stator are compared with those determined for both the design and the open (130 percent) stators.

The experimental data used for computing the performance results were obtained by conducting annular surveys of total-pressure loss downstream of the blading. Surveys were made at particular set points covering a range of velocities. The findings of reference 7 had shown the loss results to be affected by the type and location of the total-pressure probe used for loss measurements. To further investigate these findings, pressure-loss surveys for this stator were repeated at particular set points using two different design total-pressure probes located at different downstream stations. Results are shown comparing the overall loss coefficients obtained from these different loss measurements.

APPARATUS

The setting of the closed stator was determined by decreasing the channel exit orthogonal at the mean section to a value 30 percent less than that of the design stator. This change in angle setting was, of course, constant radially and resulted in a decrease at the hub and tip station exit orthogonals of 35 and 26 percent, respectively. Figure 1 presents the relative blade positions at the mean section for the design and closed

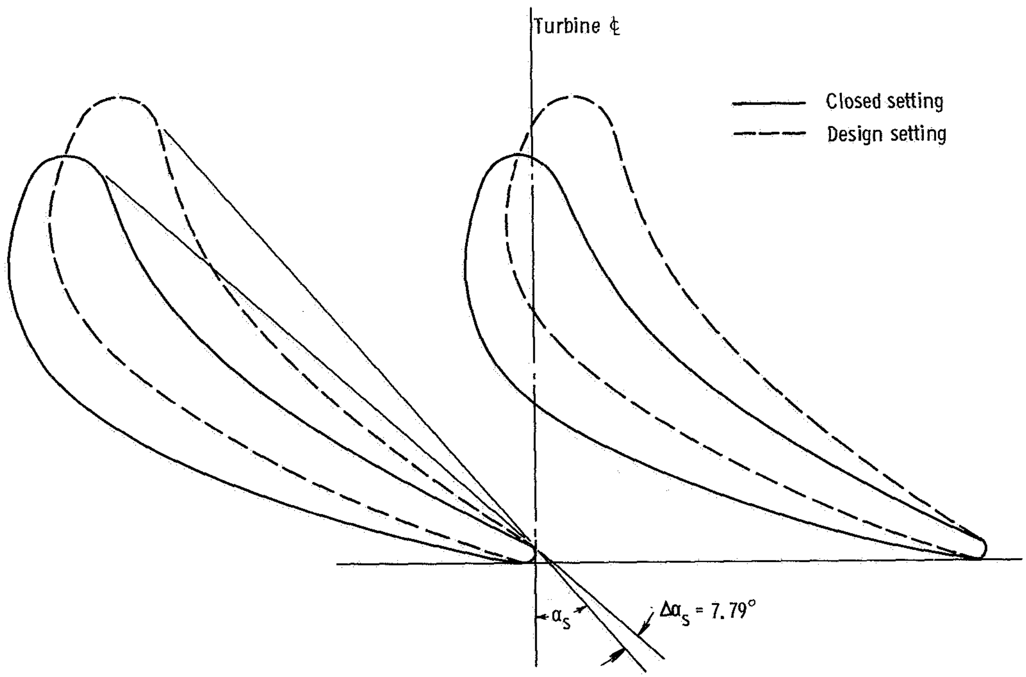


Figure 1. - Relative blade positions of closed and design area stators.

stators. The blading was oriented about the center of the trailing edges to maintain radial trailing edges for stator exit surveys. The associated stagger angle α_s was increased from 41.03° to 48.82°, a change of 7.79°. (Symbols are defined in appendix A.)

The test facility that incorporated the closed stator assembly was the same as that described in reference 4. A photograph of the stator assembly installed in the test facility is shown in figure 2, and a cross-sectional schematic of the test facility is shown in figure 3.

INSTRUMENTATION

The instrumentation used for obtaining the reported results was essentially the same as that described for the open stator (ref. 7). This instrumentation is briefly described herein.

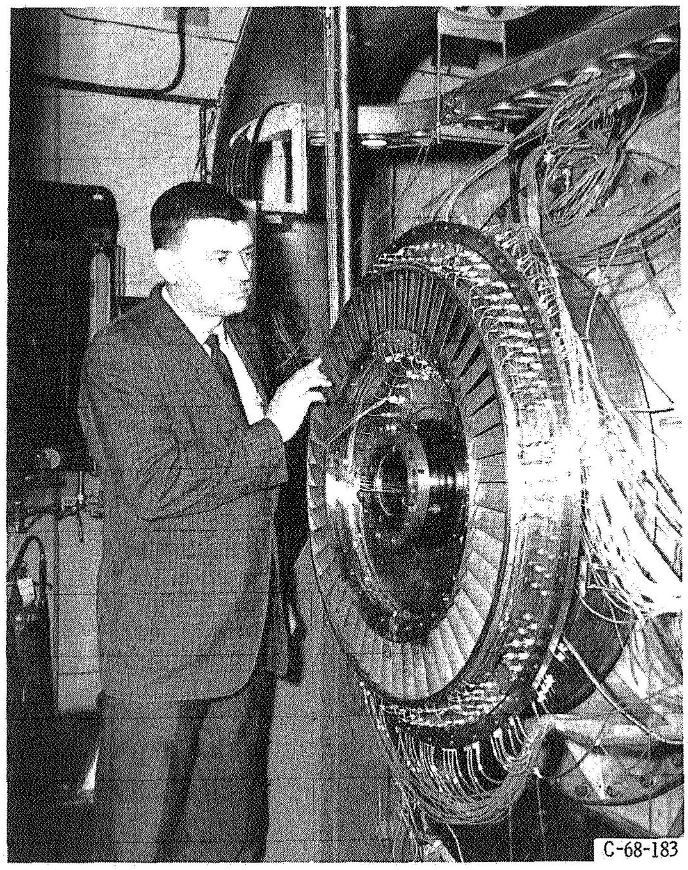


Figure 2. - Closed stator assembly installed in test facility.

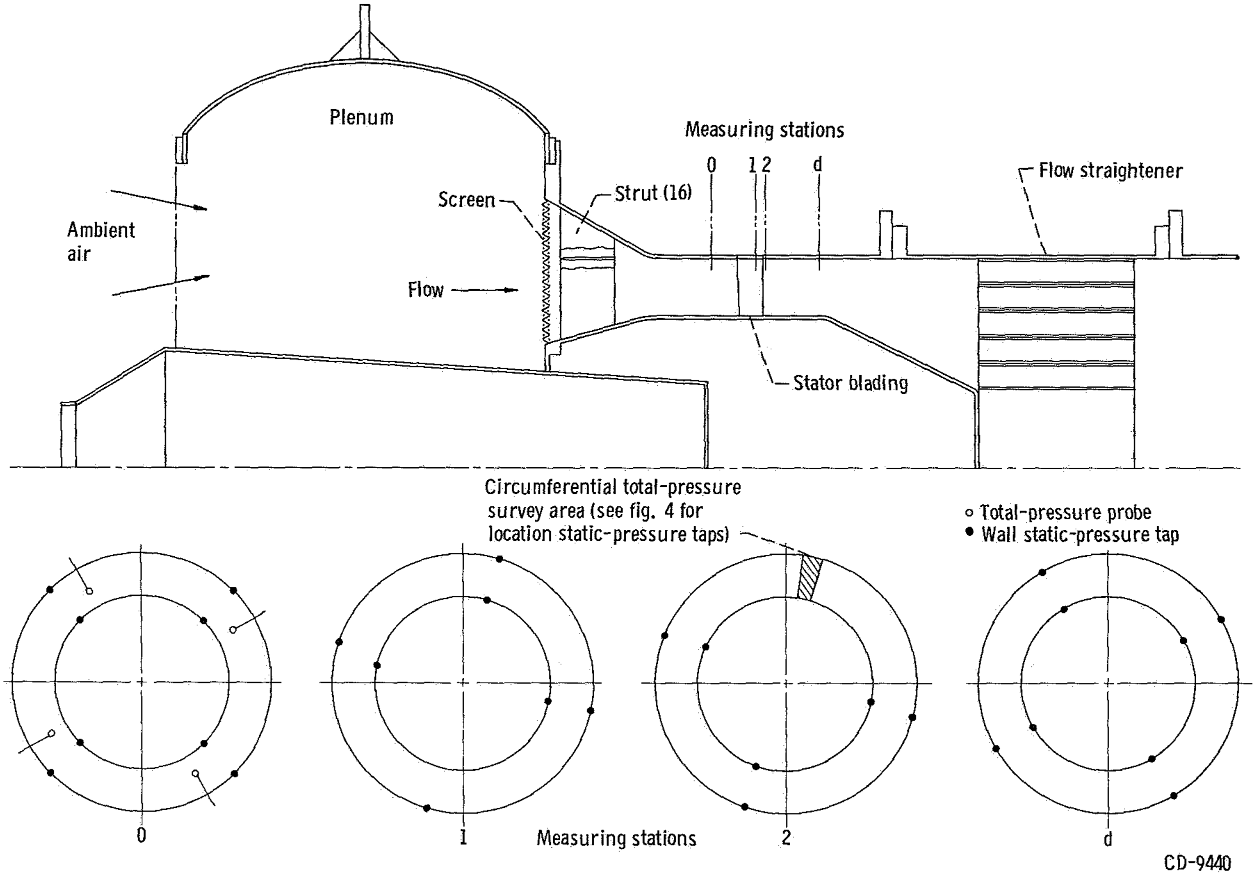


Figure 3. - Schematic diagram of stator test facility and instrumentation (looking upstream).

Pressure Measurements

The locations at which total and static pressures were measured is shown in figures 3 and 4. The inlet measuring station was located one blade chord upstream of the blade row, and the downstream measuring station was located about $2\frac{1}{2}$ blade chords behind the blade row. The inlet total pressure was measured with Kiel-type total pressure probes. The static pressure taps were conventional.

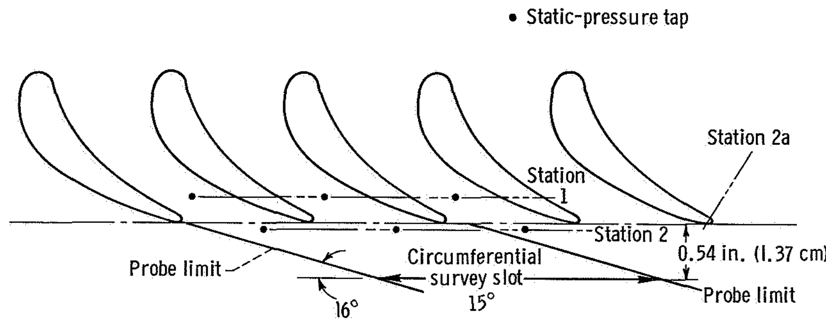


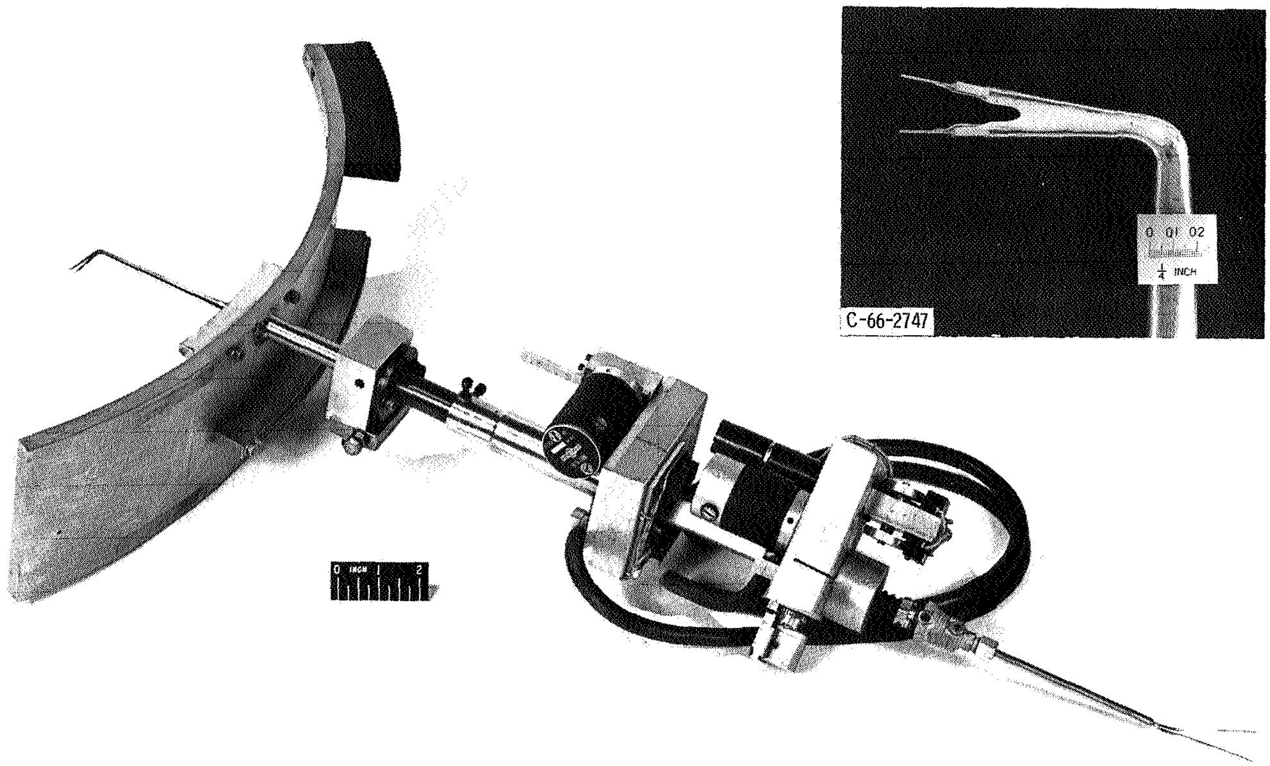
Figure 4. - Schematic circumferential survey probe travel and approximate location of inner and outer static-pressure tap in survey.

Total Pressure Survey Probes

As mentioned in the INTRODUCTION, two different design total-pressure survey probes were used in this investigation. These probes are termed the original and modified design probes.

An original design probe, actuator, and saddle assembly is shown in figure 5(a). The probe has two tubes for sensing elements. These were required for both the original and modified probes to obtain measurements at the inner and outer walls. For the original design probe, the ends of the sensing elements were of 0.012-inch (0.030-cm) outside diameter and 0.006-inch (0.015-cm) inside diameter tubing. As indicated in figure 5(a), the original design probe was held by a stem that was supported in the outer-wall saddle assembly. At the support point, the stem was 0.25 inch (0.64 cm) in diameter as determined by strength considerations. From the support point to its end, the stem was tapered radially in the direction facing flow to about 1/16 inch (0.16 cm) in order to minimize flow blockage.

The modified probe is shown in figure 5(b) before trimming the ends of the sensing element tubes to the length desired for surveying. The principle difference between this probe and the original probe was the smaller diameter support stem and larger diameter sensing elements. The support stem for this probe was of constant 0.100-inch (0.254-cm) diameter tubing and the sensing element was of 0.020-inch (0.051-cm) outside diameter and 0.015-inch (0.038-cm) inside diameter tubing. In order to reduce the diameter of the support stem for the modified probe and still maintain adequate strength, it was necessary, as indicated in figure 5(b), to support the stem at both the inner and outer walls. The inner-wall support was provided by an inner saddle assembly, which was self supporting and moved circumferentially with the outer saddle assembly. The outer-wall support was provided by the same outer-wall saddle assembly as used for the original probe.



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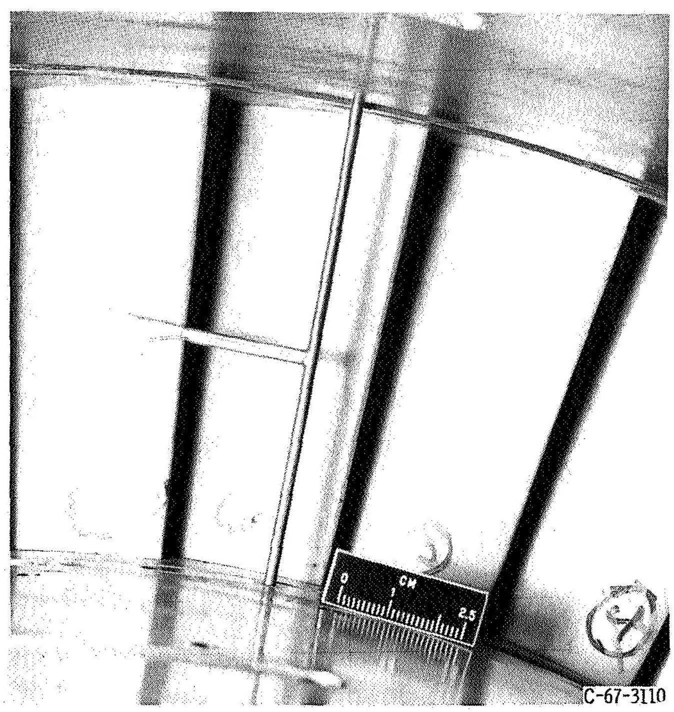
(a) Original probe.



(b) Modified probe.

Figure 5. - Photographs of total-pressure survey equipment.

TEST PROCEDURE

The same test procedure was followed for the subject closed stator investigation as that described in references 4 and 7. Ambient air was used at the inlet of the stator for all tests. The downstream stator-blade-hub static pressure at measuring station d (see fig. 3) was maintained constant for each set point to provide inlet-total- to downstream-static-pressure ratios corresponding to hub downstream critical velocity ratios of 0.5, 0.7, 0.9, and 1.1. At a particular set point, annular surveys of total-pressure loss were conducted for approximately one blade pitch at one of four different downstream measuring stations using either an original or modified design probe as described under INSTRUMENTATION. Specifically, at set points corresponding to hub downstream critical velocities of 0.5, 0.7, 0.9, and 1.1, pressure-loss measurements were made with modified design probes at two stations located approximately 0.1 inch (0.25 cm) and 1.0 inch (2.5 cm) downstream of the trailing-edge stagnation point in the direction of flow. In addition, at a hub downstream critical velocity ratio of 0.9, measurements were made both with a modified probe at a location approximately 0.6 inch (1.5 cm) downstream of the trailing edge and with original design probes at two locations approximately 0.1 inch (0.25 cm) and 0.5 inch (1.3 cm) downstream of the trailing edge. During the testing, the probes were set at an experimentally predetermined average flow angle of 16° measured from tangential (see fig. 4).

CALCULATION PROCEDURES

The experimental results reported herein were computed using the method of reference 10. This reference treats blade row losses in terms of boundary-layer param eters and includes a method for computing mixing loss.

The theoretical results reported herein were computed from the methods of references 10 to 14. Theoretical mixing loss is considered in reference 10; the prediction of three-dimensional blade row losses from mean-section blade loss is considered in reference 11; the loss due to the trailing edge of airfoils is included in reference 12; and the surface friction loss arising from laminar and turbulent boundary layers is included in references 13 and 14.

The theoretical method of reference 15 had been used to compute the blade-surface friction loss reported in references 4 and 7 for the design and open stators. An unpublished method based on the theory of references 13 and 14 is more recent and generalized than that of reference 15. It considers both laminar and turbulent boundary layers and transition from laminar to turbulent flow; whereas the method of reference 15 assumes a turbulent boundary layer for the whole surface.

BASIS OF RESULTS

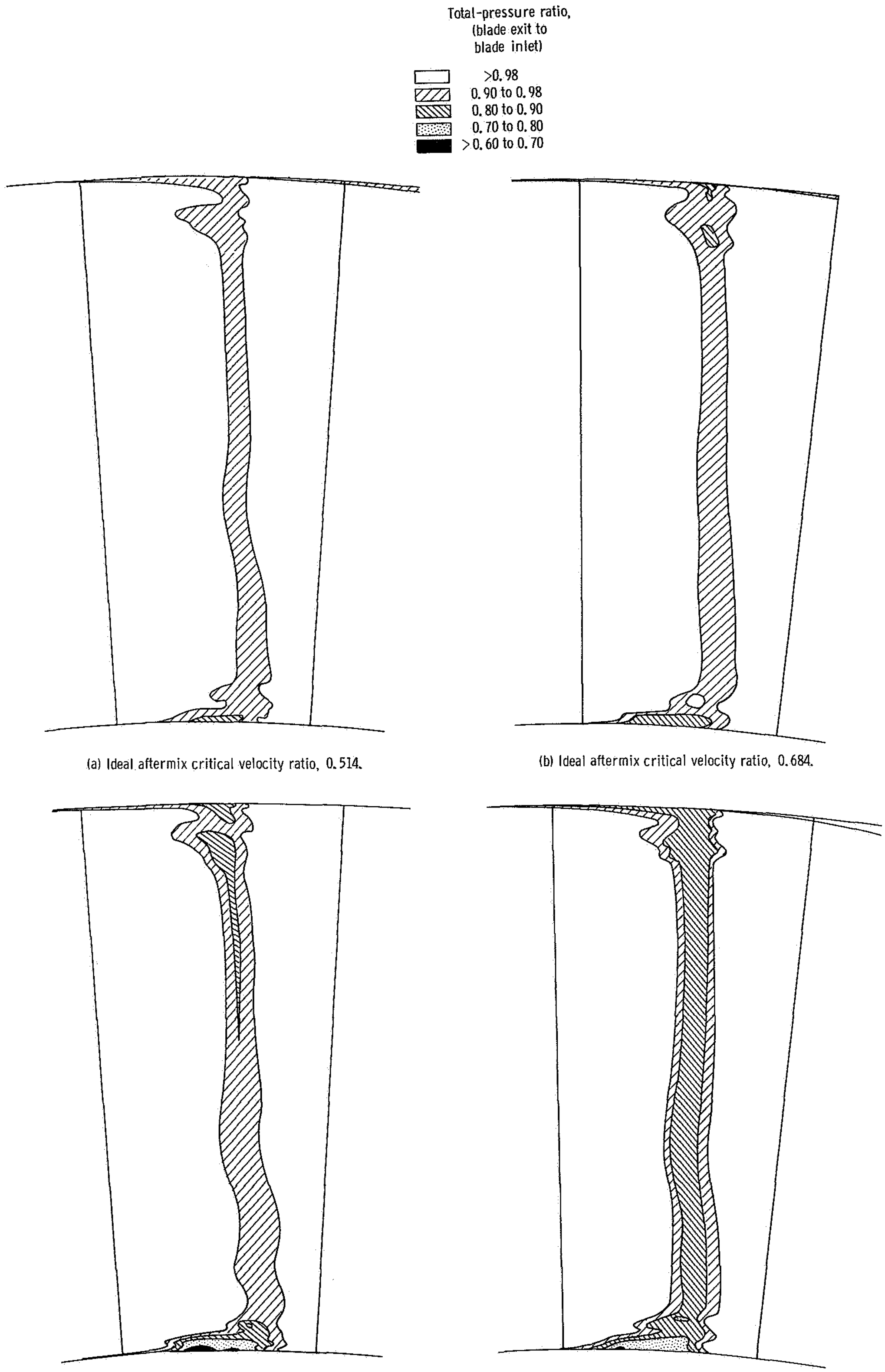
The results of reference 7 showed that, for this type of blading with thick trailing edges, overall loss coefficients obtained using a probe having too small a diameter sensing element too close to the trailing edge are higher than actual. To confirm these results, losses were obtained for the subject closed stator using two different design probes having different diameter sensing elements (see INSTRUMENTATION) located at several different downstream stations (see TEST PROCEDURE). The results of these tests, which are presented in appendix B, confirm and supplement the findings of reference 7; that is, the validity of measured losses are independent of the locations tested for the modified probe, but are dependent on the locations tested for the original probe. Therefore, the design stator, which was initially tested using an original probe, was retested using a modified probe to provide a consistent basis of comparison for the three stator settings. This retest showed that the overall loss coefficients for the design stator reported in reference 4 using an original probe are about 0.020 higher than actual.

RESULTS AND DISCUSSION

Experimental and analytical loss coefficients as a function of velocity level were obtained for the closed stator and compared with values obtained for both the design and open stators. The results are presented in four sections. The first section presents the experimental results of the closed stator. The second section then compares the experimental and analytical results for the closed stator. The third section compares the experimental results for the closed stator with results obtained for the design and open stators. The last section then compares both the experimental and analytically predicted results for the closed stator with corresponding results obtained for the design and open stators.

Experimental Results of Closed Stator

The experimental results presented include annular sector contour plots of total-pressure loss across the blade row, variations in loss parameters with radius, and a summation of mean-section and annular-sector kinetic-energy loss coefficients. The kinetic-energy loss coefficient $\bar{e}$ expresses the loss in kinetic energy as a decimal part of the ideal kinetic energy of the actual flow at the station under consideration. Efficiency, on a kinetic-energy basis, may be obtained by subtracting this coefficient from unity.



(a) Ideal aftermix critical velocity ratio, 0.514.

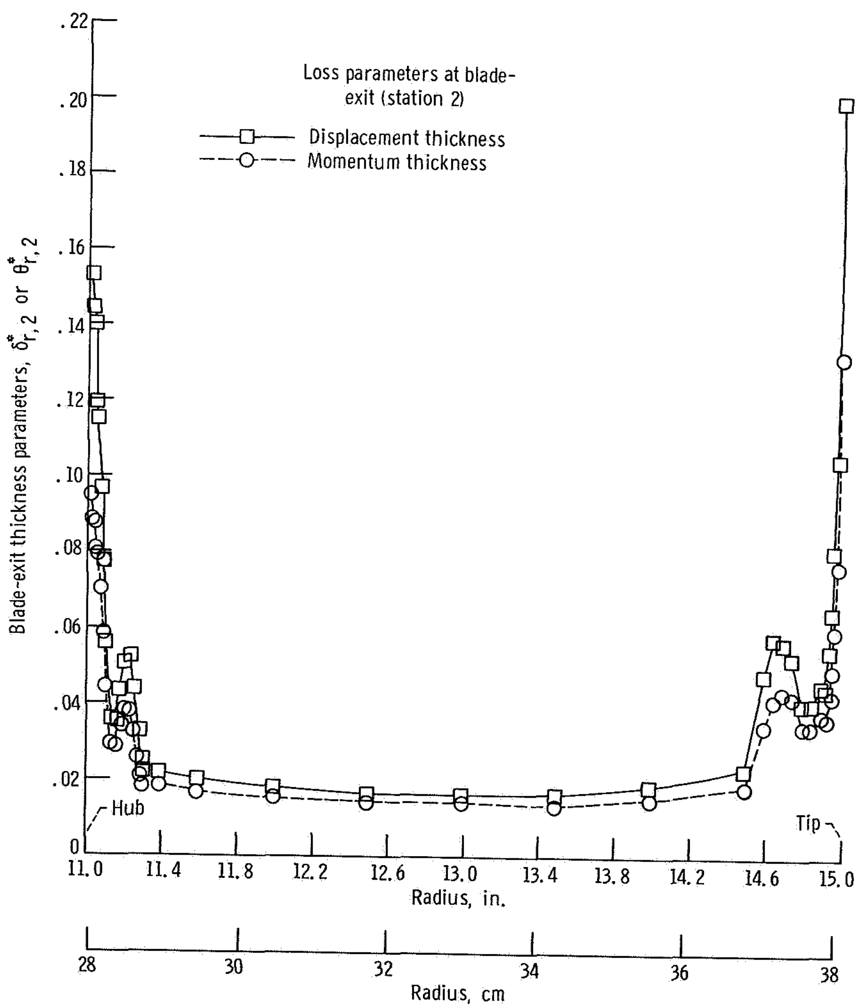
(b) Ideal aftermix critical velocity ratio, 0.684.

(c) Ideal aftermix critical velocity ratio, 0.848.

(d) Ideal aftermix critical velocity ratio, 0.923.

Figure 6. - Contours of total-pressure ratio from annular surveys.

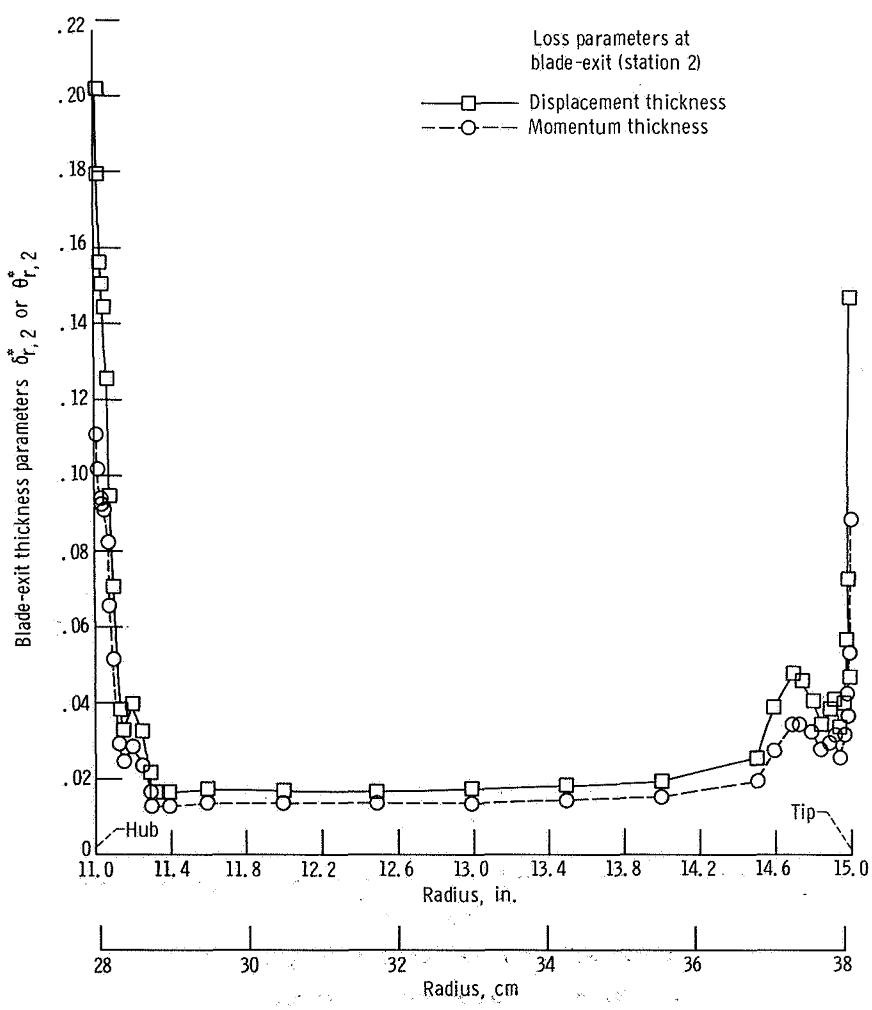
Total-pressure ratio and boundary-layer parameters. - The contour plots of total-pressure ratio across the blade row p_2'/p_0' are shown in figure 6 for the range of velocity levels investigated. Although such plots do not give quantitative losses as a percentage of ideal kinetic energy, the results shown indicate good blade performance as a function of both radius and velocity level. Near the inner and outer walls there are small loss cores. Such cores are conventional and result from secondary flow in which some of the high loss end wall fluid moves from the walls to the blade surface and accumulates in the low-pressure area on the suction side of the blading. The absence of loss cores away from the end walls indicates that, for most of the blade span, the flow was attached at the blade trailing edge and that there were no appreciable movements of secondary flows.



(a) Mean-section ideal aftermix critical velocity ratio, 0.514.

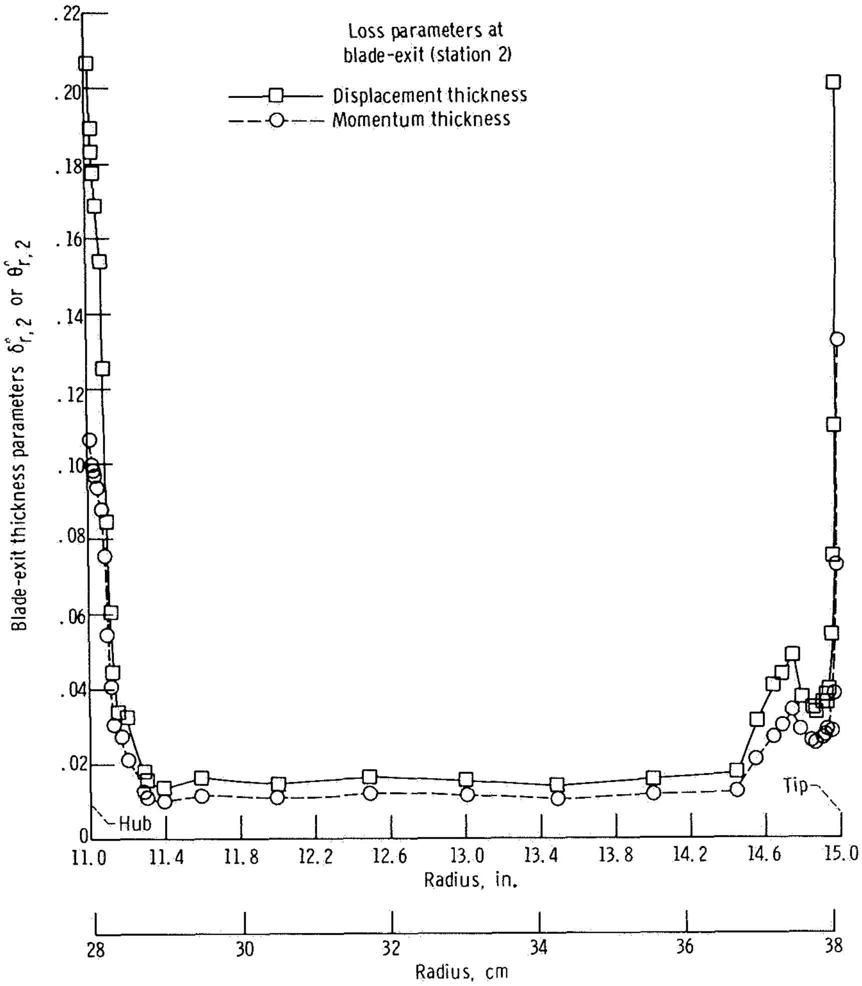
Figure 7. - Variation in blade-exit thickness parameters with radius.

The radial variations in displacement thickness parameters $\delta^*_{r,2}$ and momentum thickness parameter $\theta^*_{r,2}$ at the blade outlet for a range of velocity levels are presented in figure 7. The displacement parameter expresses the loss in flow as a decimal part of the ideal flow without blockage. The momentum parameter expresses the loss in momentum as a decimal part of the momentum of the ideal flow without blockage. The variation in these parameters with radius is an indication of the radial variation in blade performance. The trends of figure 7 are similar at each of the critical velocity ratios investigated. There is the expected buildup of losses at both the hub and tip regions because of the combination of blade surface loss, trailing-edge loss, and end wall loss. At radii removed from the end walls by about 0.5 inch (1.27 cm) and more, the trend indicates a nearly constant value of low loss from hub to tip. This indicates a favorable blade loading along the span of the blade with the mean section being representative of the entire blade.



(b) Mean-section ideal aftermix critical velocity ratio, 0.684.

Figure 7. - Continued.



(c) Mean-section ideal aftermix critical velocity ratio, 0.848.

Figure 7. - Concluded.

Kinetic-energy loss coefficients. - The variation of kinetic-energy loss coefficients with velocity is shown in figure 8. Both mean and annular sector coefficients are shown by the three curves of the figure. The lower curve of $\bar{e}_{2,m}$ represents the blade mean section losses resulting from surface friction, trailing edge, and any mixing occurring between the trailing edge and the downstream measuring station. The middle curve of $\bar{e}_{2,3d}$ includes the same losses as the lower curve of $\bar{e}_{2,m}$ and, in addition, the three-dimensional effects of the end wall losses and any variation in blade surface loss from that occurring at the mean section. Finally, the upper curve shows the overall stator loss in terms of aftermix annular sector kinetic-energy loss coefficients $\bar{e}_{3,3d}$. This overall loss includes the losses of the middle curve $\bar{e}_{2,3d}$ plus the mixing loss between measuring station 2 and the aftermix condition at station 3.

Figure 8 indicates total blade row losses from about $3\frac{1}{2}$ to $4\frac{1}{2}$ percent of available kinetic energy, with a slight decrease in loss with increasing velocity.

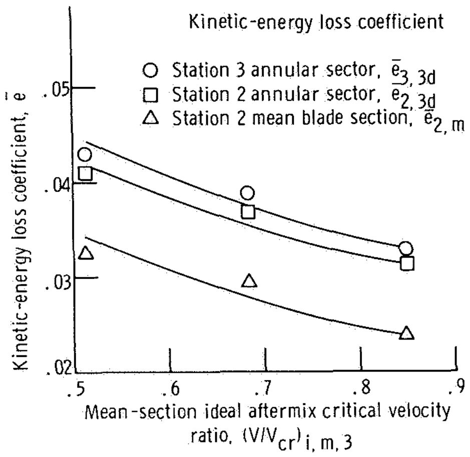


Figure 8. - Variations of loss coefficients with velocity for closed area stator.

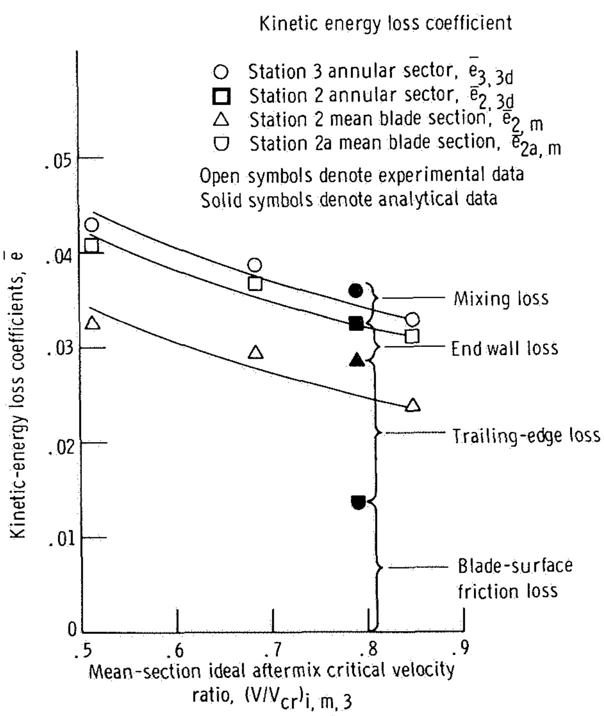


Figure 9. - Comparison of analytically predicted loss coefficients with experimental loss coefficients for closed area stator.

Comparison of Experimental and Analytical Results for Closed Stator

The analytical results for the closed stator are presented in figure 9. As evident, this figure is a repeat of figure 8 (experimental results) with corresponding analytical values inserted as solid data points for comparison. It will be noticed that experimental values of blade surface friction loss $\bar{e}_{2a,m}$ were not obtained for this stator setting.

The figure shows that the overall loss $\bar{e}_{3,3d}$ was predicted to be very close to that determined experimentally. Furthermore, the largest difference shown on the figure between corresponding experimental and analytically predicted loss coefficients is about 0.004. This is considered good agreement because the accuracy of the experimental data, estimated to be about ±0.0025, is about as large as this difference.

The large value of indicated trailing-edge loss should be noted. Assuming that the predicted value for trailing-edge loss of 0.0150 is correct, then roughly 45 percent of the overall blade row loss results from a trailing-edge blockage constituting about 15 percent of the flow area.

Comparison of Experimental Results at Different Stator Area Settings

Figure 10 compares the experimental results for the three stator area settings considered in the variable stator area phase of investigation. There is some scatter in the results, but a single curve has been drawn to represent the loss for the three stator settings. The single curve was drawn because the scatter is probably within the limits

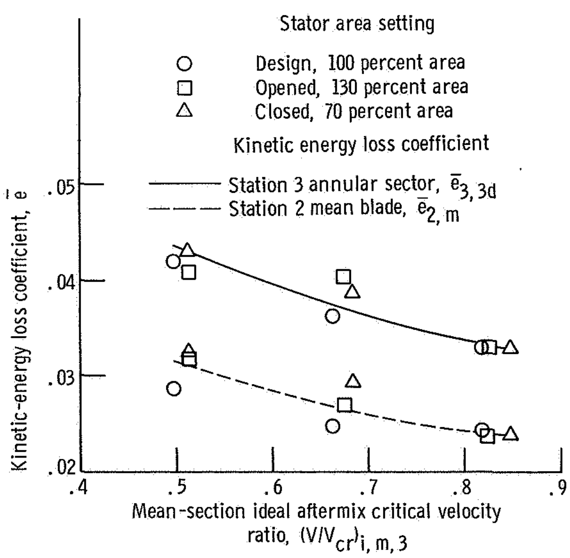


Figure 10. - Comparison of experimental loss coefficients for different stator area settings.

of the absolute accuracy of the test data. The general conclusion of the variable stator area investigation is, therefore, that the overall loss of the stator was about the same (0.035 to 0.045) at the three settings for the range of exit velocity considered. Some theoretical reasons why the level of performance of the stator would be expected to be about the same at the different settings is given in the following section.

Comparison of Experimental and Analytical Results at Different Stator Area Settings

Figure 11 compares the experimental and analytical loss coefficients for the three stator area settings at the design velocity ratio of 0.790. Three different losses are compared in the figure. The upper two curves compare the experimental and analytical values of overall loss coefficients; the middle curves compare the mean-section blade surface and trailing edge loss; and the lower two curves compare the mean-section blade surface friction loss. Considering the estimated test accuracy, the agreement shown between experimental and analytical results for all three stator settings is considered good. It is concluded that the four analytical procedures referenced and discussed under CALCULATION PROCEDURES for obtaining either blade surface friction loss, trailing-edge loss, three-dimensional loss, or mixing loss closely predicted the separate and overall loss of this particular blading. It is noted, however, that this agreement may be fortuitous, and it is not known if the validity of the methods can be generalized.

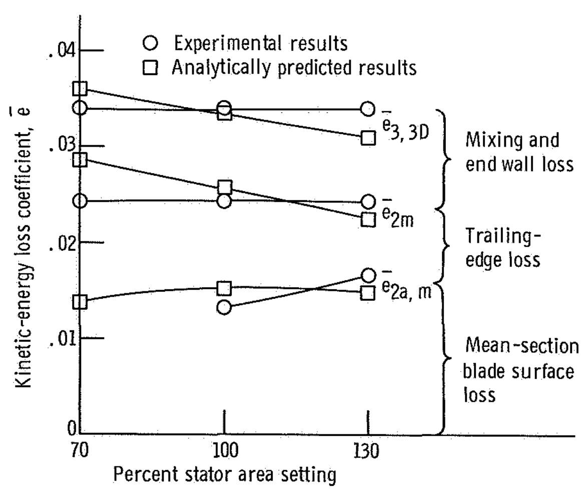


Figure 11. - Comparison of experimental and analytically predicted loss coefficients for different stator area settings at design mean-section ideal critical velocity ratio of 0.790.

The predicted results shown on figure 11 may be used to obtain a relative loss breakdown for the three stator settings. The lower analytical curve of $\bar{e}_{2a,m}$ indicates that the mean-section blade surface friction loss for the three settings should be about equal. This equality occurs because the total momentum thickness of the blading decreases with reduced stator area setting as a result of more favorable blade loading. However, because the free-stream momentum also decreases with reduced area setting, the momentum (and energy) loss as a percentage of free-stream momentum is about constant for the different settings.

The difference between the middle analytical curve $\bar{e}_{2,m}$ and the lower analytical curve $\bar{e}_{2a,m}$ predicts an increase in trailing-edge loss from about 0.008 at the open stator setting to about 0.015 at the closed stator setting. These predicted trailing-edge losses are substantial and result from a trailing-edge blockage varying from about 8 percent at a 130 percent stator setting to a blockage of about 15 percent at a 70 percent stator setting. The trailing-edge loss for this stator may then amount to about 1-percent loss in available kinetic energy for each 10 percent blockage.

Finally, the difference between the upper and middle analytical curves of $\bar{e}_{3,3d}$ and $\bar{e}_{2,m}$ predicts a variation in end wall and mixing loss for the three stator settings. For the same mixing loss, this difference shows a small decrease in end wall loss from about 0.0085 at the open stator setting to about 0.0075 at the closed stator setting. This results from a decrease in end wall area from the open to the closed stator setting.

In summary, the experimental results indicated no significant change in overall loss as the stator area was varied from 130 to 100 to 70 percent of design. At the design exit Mach number, the stator experimental efficiency was about 96.5 percent at all three settings. It was predicted that the overall efficiency would decrease slightly from about 97.0 percent at the open setting to about 96.5 percent at the closed setting. This 1/2 point predicted decrease is a result primarily of the larger blade trailing-edge blockage at the closed setting.

SUMMARY OF RESULTS

As part of a single-stage variable stator area turbine program, an investigation of the kinetic-energy loss coefficients of the stator in a closed setting was made. For this setting, the channel exit orthogonal at the mean section was decreased to 70 percent of that of the design area setting. Experimental and analytical loss coefficients were obtained for the closed stator and compared with similar values for the design and open stators. The results are summarized as follows:

1. The experimental value of efficiency for the subject closed stator varied from about 95.5 percent to 96.5 percent with exit velocity, the higher efficiency occurring at

the higher velocity. This agreed closely with that predicted analytically.

2. The stator performance in terms of percent kinetic-energy loss was determined to be virtually insensitive to stator area change over the range covered in the investigation. The same experimental value of efficiency of about 96.5 percent was obtained at design exit Mach number as the stator area was varied from 130 to 100 to 70 percent of design. This efficiency is close to the predicted results, which indicated a decrease in efficiency from about 97 percent to 96.5 percent as the stator was closed from 130 to 70 percent of design area. The 0.5 percent predicted decrease resulted primarily from a larger blade trailing-edge blockage in the closed setting.

3. For the particular stator blade tested, an approximate correlation of kinetic-energy loss with trailing-edge blockage was predicted and experimentally confirmed at two stator area settings; that is, over the range of stator settings covered, a decrease in efficiency of 1 percent might be expected for each 10 percent of trailing-edge blockage.

4. For this type of blading with thick trailing edges, loss coefficients obtained from data measured with a total-pressure probe that had too small a diameter sensing element and was too close to the trailing edge are higher than actual. The loss coefficients for the design stator reported in reference 4 were based on such measurements. Loss coefficients obtained from a retest of this stator using a modified design probe shows the coefficients reported in reference 4 to be about 0.020 larger than actual.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 19, 1968,
720-03-01-35-22.

APPENDIX A

SYMBOLS

$\bar{e}$ kinetic energy loss coefficient

p pressure, lb/ft^2; N/m^2

V absolute gas velocity, ft/sec; m/sec

α_s blade orientation angle measured from axial direction, deg

δ^* displacement thickness parameter

θ^* momentum thickness parameter

Subscripts:

cr conditions at Mach 1

d station downstream used for set point

i ideal conditions corresponding to isentropic process at mean blade section

m mean blade section

0 station upstream of blade row

1 station at stator throat

2 station downstream of stator trailing edge

2a station just before stator trailing edge

3 station after complete mixing occurs

3d three dimensional or annular sector

Superscript:

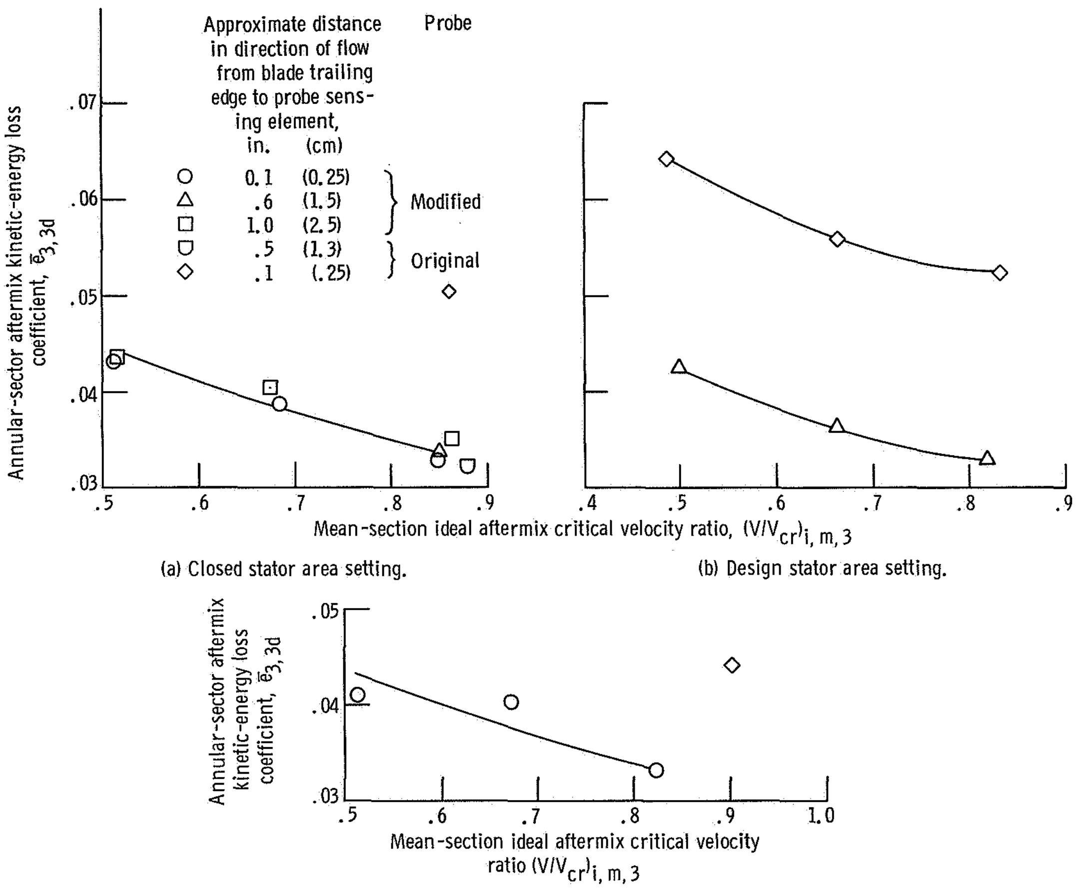
' total state

APPENDIX B

COMPARISON OF OVERALL STATOR LOSS OBTAINED WITH DIFFERENT TOTAL PRESSURE PROBES

During the investigation covering the performance of the variable area stator, evidence was disclosed which indicated that loss measured with a total-pressure probe was affected by (1) the diameter of the sensing element of the probe and (2) the distance between the probe sensing element and the blade trailing edge. To confirm these affects, losses were obtained for the three different stator area settings using measurements from two different design total-pressure probes. These probes, called the original and modified design probes, are described in some detail under INSTRUMENTATION. The principle difference between the original and modified design probes was that the modified probe had a larger diameter sensing element and a smaller diameter support stem than the original probe.

Using either an original or a modified design probe, surveys were made at several different downstream measuring stations. The overall loss coefficients obtained for the three stator area settings with the two probes at different locations are shown in figure 12. In figure 12(a), the loss coefficients obtained with the modified probe for the closed stator show good agreement for all distances from the trailing edge that data were taken. And the loss coefficients obtained with the original probe agreed well with the modified probe when data were taken away from the trailing edge. However, when the original probe was placed near the trailing edge, the obtained coefficient was larger than the others. This larger loss is also evidenced in figures 12(b) and (c) for the other two stators settings when the original probe was placed near the blade trailing edge. From these results it is concluded that, for this type of blading with thick trailing edges, the losses obtained using a probe with too small a diameter sensing element too close to the blade trailing edge are higher than actual values. This error appears to be caused by the following: Local flow around the thick trailing edge of the blading results in local flow angles relative to the probe that are greater than the angle sensitivity of a small-diameter probe sensing element that is quite close to the blade. This results in a measurement of local total-pressures that is less than actual and yields apparent losses that are larger than the actual losses. Secondly, large static-pressure gradients exist in the wake area close to the blade trailing edge as a result of the fluid near the blade surface diffusing rapidly into a region of low flow at the trailing edge and then re-expanding to free-stream conditions. This then results in the use of smaller than actual values for static pressures in the wake area and yields larger than actual losses.



(a) Closed stator area setting.

(b) Design stator area setting.

(c) Open stator area setting.

Figure 12. - Comparison of overall loss obtained from measurements with different total-pressure probes at different downstream locations.

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